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ational Meeting on Radiation Processing, Miami, 1978

RADIATION SOURCES - "E.B."

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"E.B.," Electron Beam sources, as viewed and discussed from a user's standpoint. Electron beam devices have long been talked about by many but used by few until recent years. Within the past 10 to 15 years numerous varieties of industry have begun using the Electron Beam Generator ("E.B.G.") as a production tool as often as any common production machines. The main problem with electron beam generators is the heavy capital outlay required for a complete production facility. This deters many industries from developing a product requiring high energy radiation processing.

However, this paper is not to discuss the costs required for an "E.B." installation, but rather some basic cell designs, various E.B. theories, auxiliary equipment required to operate the accelerators, installation and serviceability of various E.B. systems.

Prior to the purchase of a radiation unit by any industry or organization, an extended market study is an absolute necessity. In addition to being able to market the cross-linked product, a user must recognize the tool as one which does require service on a regular basis, as well as requiring emergency service on an irregular basis. Through this report I hope to show the realistic side of being an E.B. owner and processor.

First we shall have a look at the many types of electron beam generators, the basic theory of operation and the types manufactured for industrial use. All generators must have a three-phase A.C. power input with some form of regulation to a driving transformer or power supply which then develops a high voltage for electron acceleration through a voltage divider or cascading media.

Figure 1 shows a Cockcroft-Walton generator which is probably one of the oldest types, usually air insulated and consists of basically two sections, both containing a high voltage terminal. The first unit is the cascade rectifier and capacitor assembly through which the D.C. high voltage is built and stored on the terminal. This voltage is then applied to a second unit along with an A.C. voltage for heating a filament in the high voltage end of an evacuated, multistage insulated tube through which the electron beam is accelerated. To the best of my knowledge this type of accelerator was not mass produced and is not practical for industrial applications.

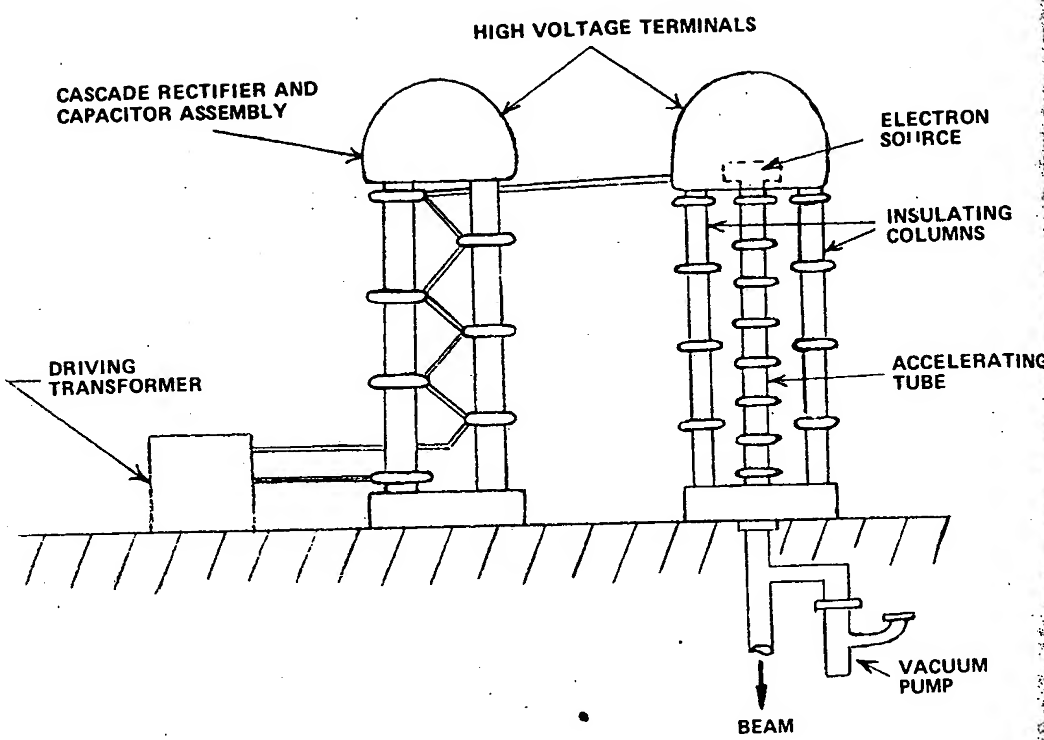

Fig. 1. Cockcroft-Walton generator.

Figure 2 is the schematic for a linear accelerator, more commonly known as a Linac. These units are manufactured by several companies for industrial, medical and research use, and are desirable not only for their versatility for electron and ion production but also for their capability to produce high voltages and current. The machine is fairly efficient and operates by regulating an A.C. input, modulating the input and feeding the resulting pulse to a microwave power tube. The high voltage is then applied to an evacuated waveguide for electron beam acceleration. This waveguide can be extremely long for very high energy applications. The main drawback in using this type of equipment in an average industrial facility, with unskilled labor, is the buildup and scattering of X-rays and the effect of sky-shine. This makes the radiation field intensity outside the shielding of high-powered Linacs difficult and uncertain to predict, not a practical situation for a heavy manufacturing facility.

Figure 3 shows a Van de Graaff® accelerator, perhaps one of the better known and understood of all generators used in the research and industrial field. All single-stage Van de Graaffs® are convertible from electron to positive ion operation. Operation is obtained by applying a charge to a neoprene-impregnated belt moving around two insulated pulleys. One pulley is the drive motor and the other is a 400-Hz alternator to power the filament circuits. Charge is applied through a screen and removed from the belt via a screen and stored on a highly polished stainless terminal which completes an electrostatic configuration known as the column assembly. Beam is generated by boiling electrons from a filament within an evacuated tube. High voltage stored on the terminal extracts and focuses the

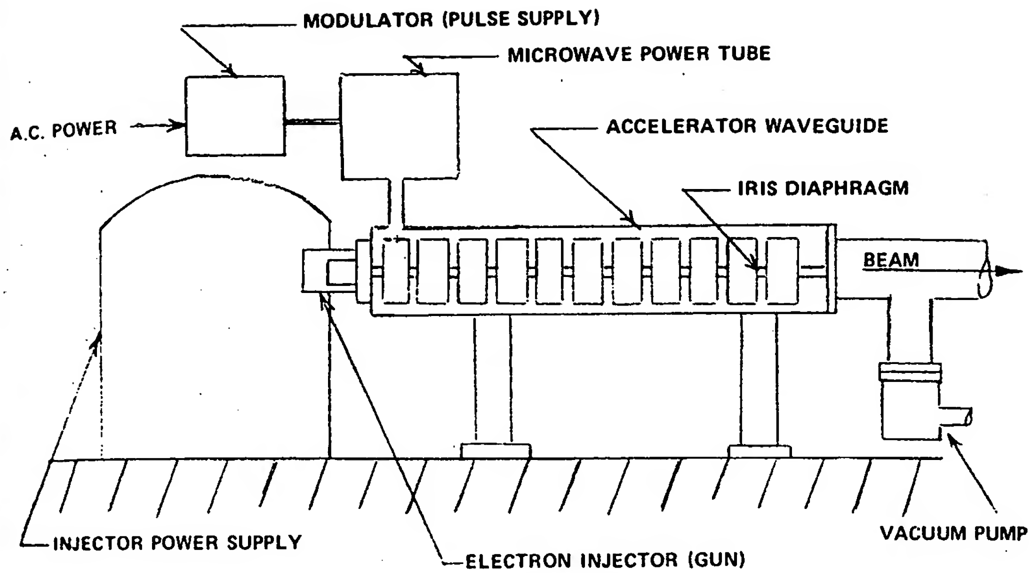

Fig. 2. Schematic - linear accelerator.

electrons, then accelerates the beam which is scanned at a given frequency and amplitude and can be adjusted to a predetermined length. The length is generally restricted due to the narrow scan angle of 37½°. The Van de Graaff® requires maintenance inside the pressure vessel approximately every 500 hours to 700 hours of operation. It is somewhat ruled out as an industrial processing tool due to its low beam capacity. Beam reduction means greatly reduced production output.

Figure 4, the resonant transformer, is the only A.C. electron beam generator made on a production basis. Manufacture of the E.B.G., as it is affectionately known, ceased nearly 20 years ago, yet many are still used in radiation production and are being repaired even though replacement parts are literally nonexistent. The E.B.G. was made only in 1 megavolt (MV) and 2 MV sizes for X-ray and electron production. The stack or high-voltage transformer, although made up of many thin [illegible] transformer sections and held in compression with prestressed glass rods, is [illegible] a single unit and is handled as one component. Excitation of the stack [illegible] accomplished by 180 Hz variable A.C. voltage applied to a primary coil which [illegible] induces voltage to the stack. The top coil supplies A.C. for filament [illegible] the remaining stack coils are connected to tube electrodes and copper [illegible] and alternately pulse the beam and accelerating voltage from 1 MeV or [illegible] ground. The filaments, unlike those in D.C. generators, are helical [illegible] opposed to a hairpin and are made of tantalum or tungsten. As A.C. [illegible] applied to the filament, a pulse is alternately applied to a grid down- [illegible] the electron gun. This allows the electrons to "pulse" through the [illegible] through a focusing field and scan coils. The maximum scanned beam [illegible] in. and passes through a seven-mil titanium window. All other accel- [illegible] replaceable components, whereas the resonant beam tube, drift tube, [illegible] vacuum pump are one integral component. Main power for the resonant [illegible] always obtained from a motor generator which consists of four units: [illegible] A.C. drive motor, 180 Hz alternator, a D.C. exciter and a D.C. [illegible] control power.

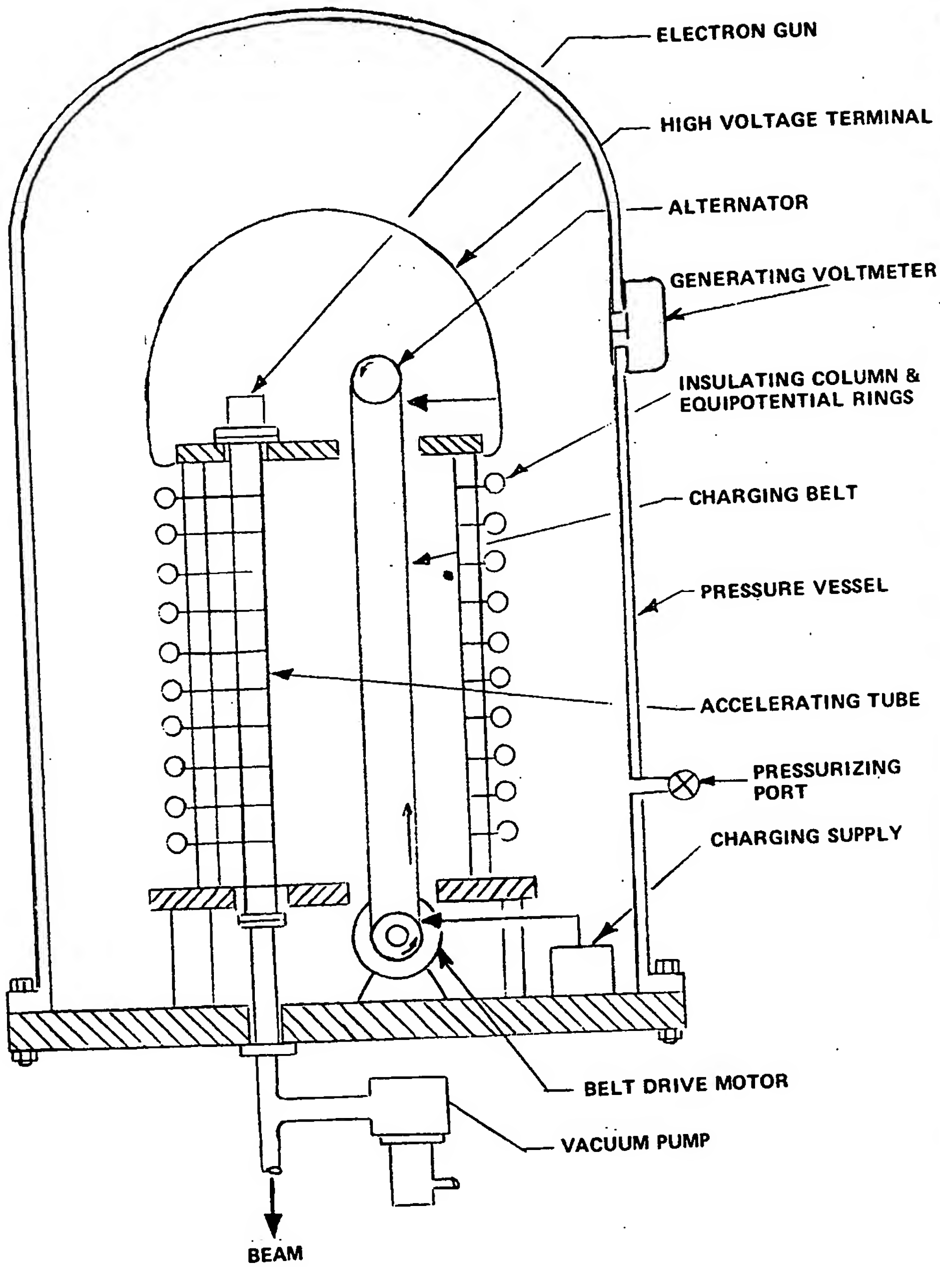

Fig. 3. Schematic - Van de Graaff® accelerator.

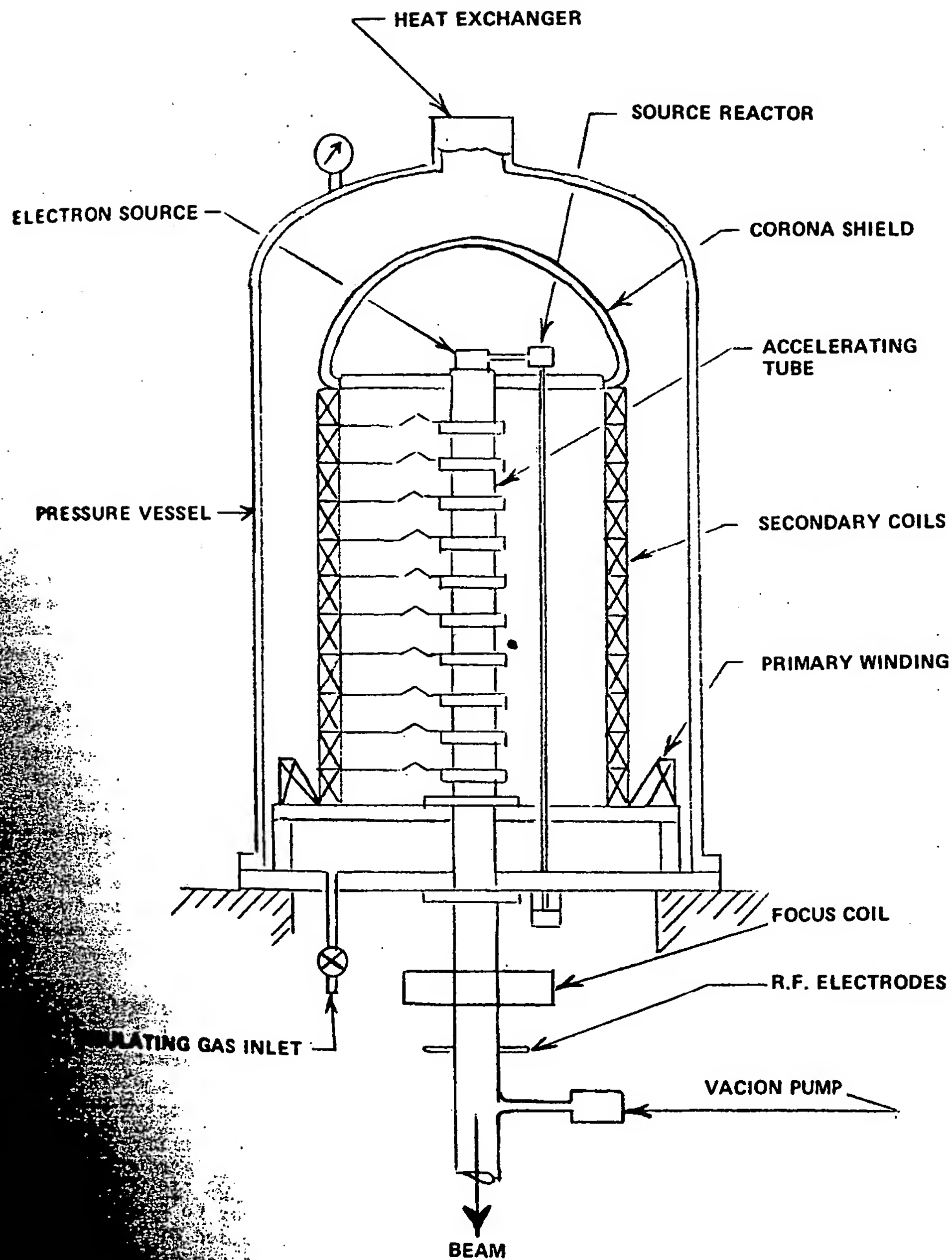

Fig. 4. Schematic - resonant transformer.

The most significant achievement of the resonant unit is the very long trouble-fr production hours. The primary drawbacks of this equipment are the restrictive scanned beam width and low beam output. Due to the manufacturer's decision to stop the manufacture of the E.B.G. some years ago, none of the modern features attractive to industry were built into the accelerators or systems.
(Slides)

The Symmetrical Cascade Generator is a D.C. accelerator power supply which provid both a high voltage and high current capability at low ripple voltage. Admittedly I know very little about this equipment except that it is similar to the Cockcrof Walton and has been fabricated in both air and pressure insulated designs. The unit obtains its power from a frequency converter and motor generator operating at 10 kHz.

The previous equipment descriptions were deliberately brief, as the emphasis will be on accelerators discussed later in this paper.

Present-day industry is interested in electron beam accelerators with energy level from 300 KV to 4 MV and high output currents. Today's product lines range from 1 mil to 200 mil in thickness and require the appropriate penetrating energy with a current output for high-speed processing. The purchase costs of the electron generators, housing facilities and ancillary equipment are indeed considerable; therefore, the proper unit must be examined for optimum product match and installed with maximum beam-to-product efficiency. In order to obtain this "match," careful studies must be made; however, there is absolutely no substitute for experience. Unfortunately, new users to the radiation business do not always have in their employ personnel with the expertise required to design a proper facility, whether it be a locally shielded unit or housed in a separate cell. Accelerator manufacturers do offer assistance in equipment selection and complete turnkey systems.

I feel a detailed study of the remaining electron sources and associated equipment is most important, as it is done with emphasis on industrialization, which as you all know is one of the main reasons for this conference. As I stated earlier, the electron beam sources to be discussed, with their varying characteristics and auxiliary systems, should be of interest to present users and informative to futu users in the selection of an accelerator for their particular product application

Figure 5 shows the schematic of a device called a Dynamitron® which is manufactur in numerous configurations with various voltages ranging from 300 kV to 4 MV with currents to 100 mA. The major component parts of a Dynamitron® are the pressure vessel assembly, R.F. oscillator, scan and control systems.

In the schematic it may be seen that the high voltage generating components are an R.F. transformer, a rectifier array, a capacitance formed by the R.F. electrodes and corona rings, and a high voltage terminal. The R.F. transformer or solenoid coil as it is more commonly known, the accelerating tube, vessel cooler, circulating blowers, rectifiers, corona rings, electron gun and beam drive are all located within the pressure vessel.

In principle, the oscillator, in conjunction with the high "Q" resonant circuit located within the pressure vessel, converts line input power to high voltage R.F power. This resonant circuit comprises an inductance, provided by the R.F. tran former, and a capacitance formed by the R.F. electrodes and the corona rings surrounding the column of rectifiers. When an R.F. potential is applied to the transformer primary, it delivers a high R.F. potential from the secondary to the R.F. electrodes. The field formed by these electrodes impresses an R.F. potenti on each of the solid-state rectifier modules by way of the capacitance coupling between the electrodes and corona rings. This arrangement provides a parallel

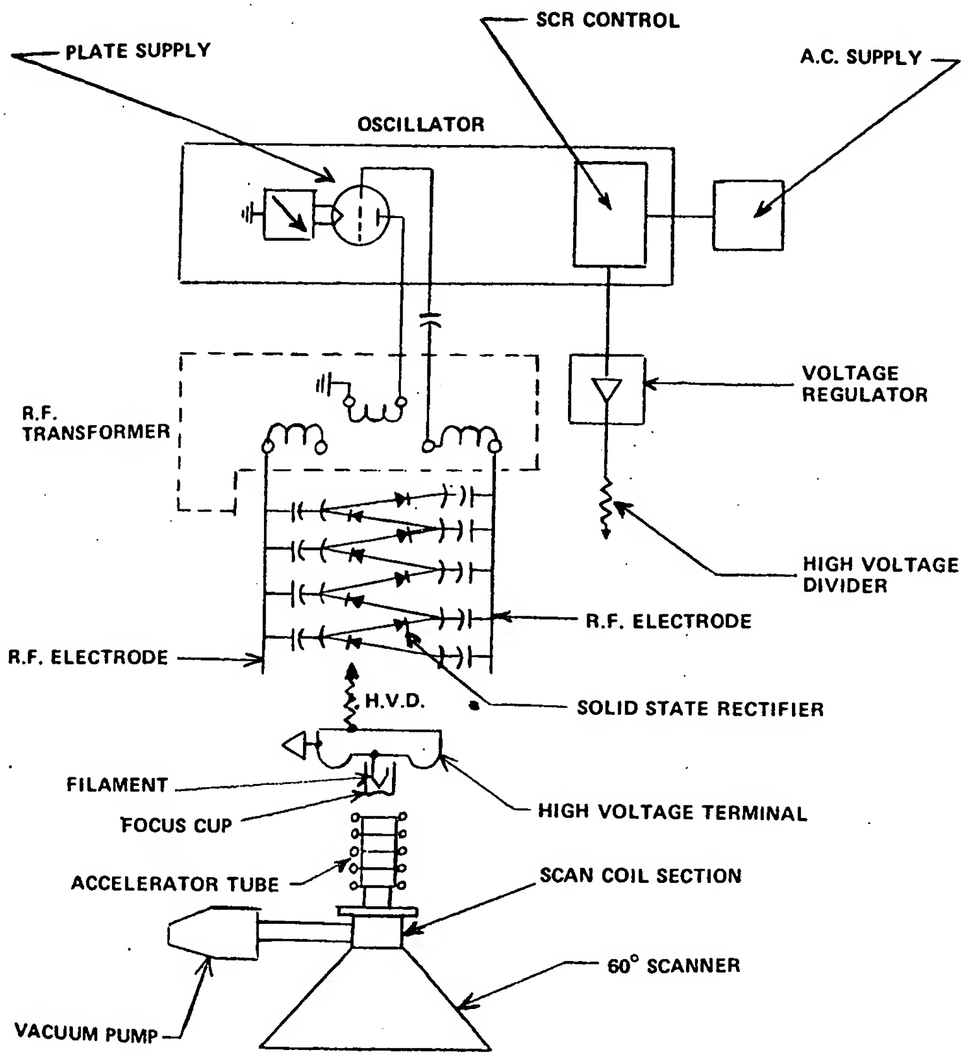

Fig. 5. Schematic - Dynamitron®.

feed to the rectifiers, which are connected in series, and consequently their D.C. outputs become additive to produce the required accelerating voltage at the high voltage terminal. The magnitude of this voltage is determined by the number of rectifier stages in the array.

The accelerator tube is directly connected to the high voltage terminal and is constructed from alternate stainless steel dynodes and glass insulators maintained under a high internal vacuum. The dynodes are connected electrically by a series of resistor strings which ensure a uniform accelerating field along the length of the tube. Internal protection is provided by shaping the metal dynodes to provide shielding from X-ray bombardment.

Electrons are produced from an electron gun mounted at the high voltage end of the accelerator tube. The unit is of fixed focus design with a directly heated filament, mounted on ceramic terminals affixed to a metal plate. Power for the filament is obtained by controlled R.F. coupling to a transformer which in turn heats the filament. By varying the filament current, the beam current delivered by the accelerator may be increased or decreased. The beam exiting from the tube anode is a well-defined stream of electrons ready for scanning.

Upon exiting the accelerator tube, the electron beam is scanned to a preset length. This is accomplished by submitting the beam to an oscillating electromagnetic field in the upper section of the scan chamber. This chamber is attached to the apex of a triangular stainless steel vacuum housing known as the scan horn. It has a thin metal window, vacuum sealed, across the opening located at the base of the triangle. The length of the window opening determines the scan length. The width is 5 cm. (Slide)
The window is fabricated from titanium thin enough to allow the electrons to pass through it. Air cooling is necessary to dissipate the heat from absorbed electrons; this is accomplished by directing a uniformly distributed air stream across the window, from a plenum fed by a low-pressure, high-volume compressor located outside the radiation area. The window can easily be replaced should a vacuum leak or implosion occur. It is sealed with a metal "O"-ring and held in compression with a series of bolted flanges. The window cooling system will be discussed later in this paper.
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As previously mentioned, all accelerating tubes must have a high vacuum maintained internally in order to accelerate the electron stream. This is accomplished in a number of ways in various accelerators through the use of vacion, triode, turbomolecular and, on rare occasions, oil diffusion pumps. Years ago the diffusion system was used extensively, but as vacuum technology became more sophisticated the trend turned more toward the turbo pump, at least in the Dynamitron®. Experience has shown that turbo pumps are fast, quiet and obtain very high vacuums; however, not all are compatible with industrial applications, as will be described later in this paper.

Figure 6 is the schematic of an Insulated Core Transformer®, better known as an I.C.T. The combination of the I.C.T. and the accelerator (I.C.A.), is called an Electron Processing System (E.P.S.) and, though the end result is the D.C. electron beam, the principle of high voltage generation is quite different. The I.C.T. power supply operates directly from a three-phase A.C. supply line at either 50 Hz or 60 Hz. The transformer core is fabricated from thin gauge transformer steel and consists of three separate columns which are magnetically coupled at each end by toroid return yokes. A primary core and a number of thinner cores are assembled within each column for the secondary, or high-voltage generating section of the power supply. The transformer secondary consists of a number of modules (decks). Every deck contains secondary coils, rectifiers, capacitors, limiting resistors and equipotential ring segments connected in a voltage-doubler circuit. Each deck also has three such doublers, identified with each phase of the three-phase transformer and develops an output voltage of approximately 50 kV. The number of decks stacked vertically and connected in series determines the terminal output voltage and the load performance characteristics of the power supply.

The ability of the power supply to withstand discharge of the full terminal voltage to ground is assured by the use of surge protection planes. These planes, located at each end of the transformer secondary, provide the means to route transient voltage surges through the secondary safely to ground. Equal distribution to surge energy and voltage within the deck is inherent to the core structure of the I.C.T. which provides a natural low impedance, capacitive network to ground.

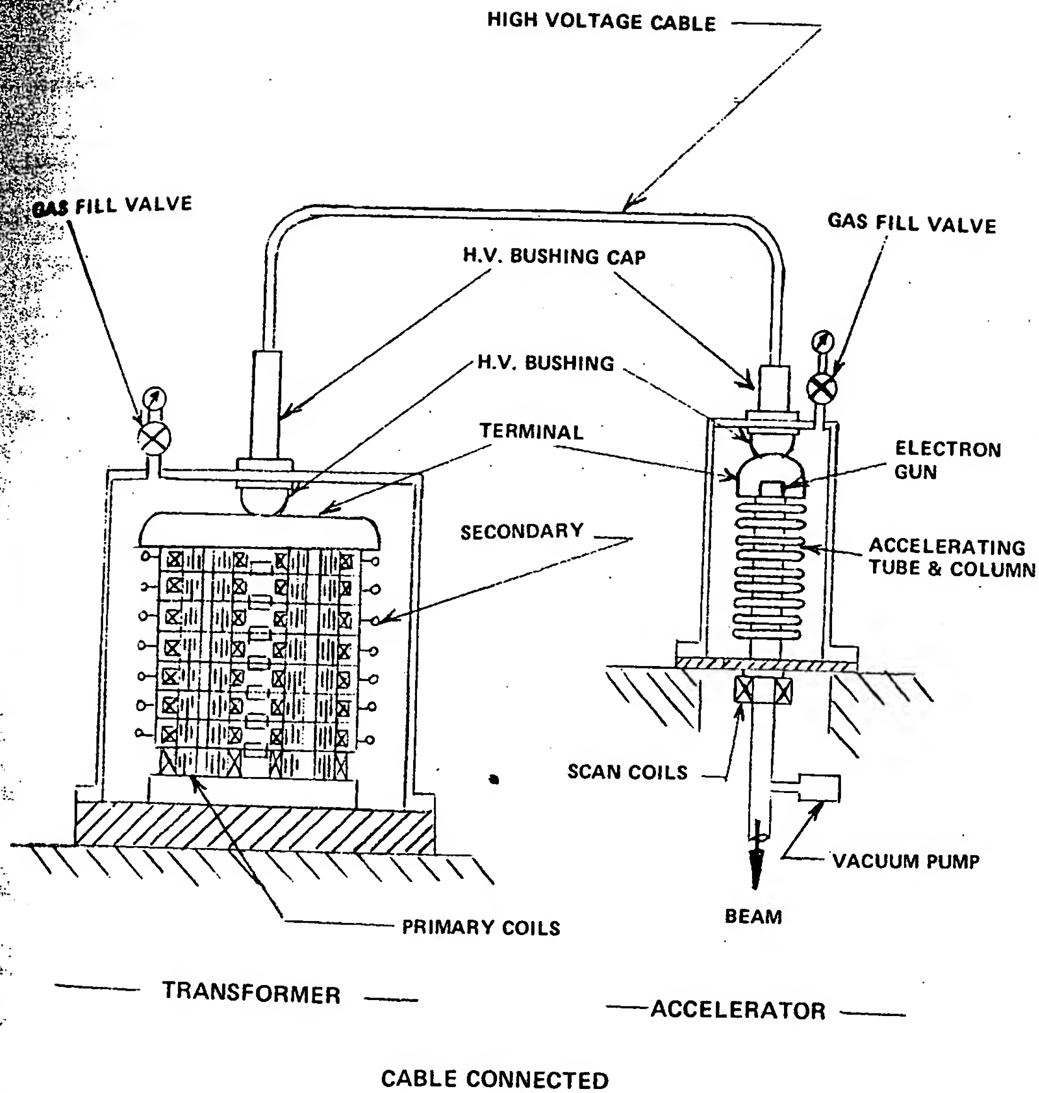

Fig. 6. Insulated Core Transformer®.

The terminal voltage of the I.C.T. power supply is connected to the cathode end of the acceleration tube. In Fig. 6 this is accomplished by means of a high voltage cable and is restricted to a maximum output D.C. voltage of 750 kV. (Slides)

The acceleration tube is constructed of glass ring insulators placed between highly polished metal electrodes. A uniform voltage gradient along the tube is obtained through the use of epoxy-encapsulated column resistors connecting each of the tube electrodes in series. The electron beam originates from a tungsten filament and is both focused and accelerated within the evacuated tube, reaching an energy corresponding to the output voltage of the power supply. This is the common method

of beam origination in all accelerators. Only the theoretical system of develop-ment varies from one to another.

After emerging from the acceleration tube the electron beam enters the stainless steel scan chamber where it is subjected to a varying electromagnetic field, causing it to be deflected at a fixed frequency. The beam then passes through a titanium window in much the same manner as described in the Dynamitron® section.

In Fig. 7 we see the schematic of an integral I.C.T.; that is to say, the acceler-ator and I.C.T. power supply are housed in one pressure vessel as opposed to the lower voltage, cable connected, power supply to the accelerator. In the integral unit, the high voltage power supply is supported over the acceleration section by insulated glass support columns. The accelerator tube, column resistors and tube resistors are packaged neatly under the high voltage terminal of the power supply. The high voltage terminal location should be clarified here. In the cable-connected I.C.T. the terminal is on top of the assembly. However, in the integral higher voltage units the terminal is on the bottom of the power supply but on top of the accelerator, which places it half-way down the vessel interior.
(Slides)

<u>Controls.</u> Obviously, electron beam generators have specific controls for the voltage and beam operation. These are, of course, supplied with the accelerator when purchased from the vendor, but they are only part of the story in controlling a processing facility. Incorporated into the vendor's control systems are certain interlocks to protect the equipment. In order to have a completely protected facility, many more interlocks and monitors should be added. A suitable arrange-ment is to add an identical cabinet adjacent to the vendor's unit and design in all the circuitry required for remote controls and product handling equipment controls.

The importance of proper interlocks and control automation cannot be overemphasized. Radiation equipment vendors are realizing the importance of automatic voltage and beam control and are incorporating this feature.

Various system controls such as the scan power supply and vacuum pump converter or power supply develop heat which must be carried away from solid-state circuitry, or control instability and/or component failure will result. In order to avoid this it is advisable to place the chassis in separate cabinets with adequate spacing between units. It is also convenient to have the chassis on tracks. One simple method of heat dissipation is that of placing an exhaust blower at the top of each cabinet to draw air through a filtered inlet at the cabinet base. Most control cabinets supplied now are of the NEMA construction, which makes cooling fairly easy. Some manufacturers prefer water-cooled heat exchangers in the con-trol centers. However, there are several drawbacks to this type of cooling. Most production process areas are not air-conditioned or controlled for humidity, thereby causing severe moisture problems due to condensation and the possibility of leakage. My experience has been that numerous failures occur as a result of condensation drip onto electrical devices, corrosion, and cabinet oxidation.

Probably the best method of controlling operating circuit thermal-related problems is through a self-contained air-conditioned cabinet such as the type used in computer chassis.
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A convenient and well-designed control center greatly increases the equipment pro-duction on-time, requires less operator attention, and results in faster and more accurate servicing of the accelerator.

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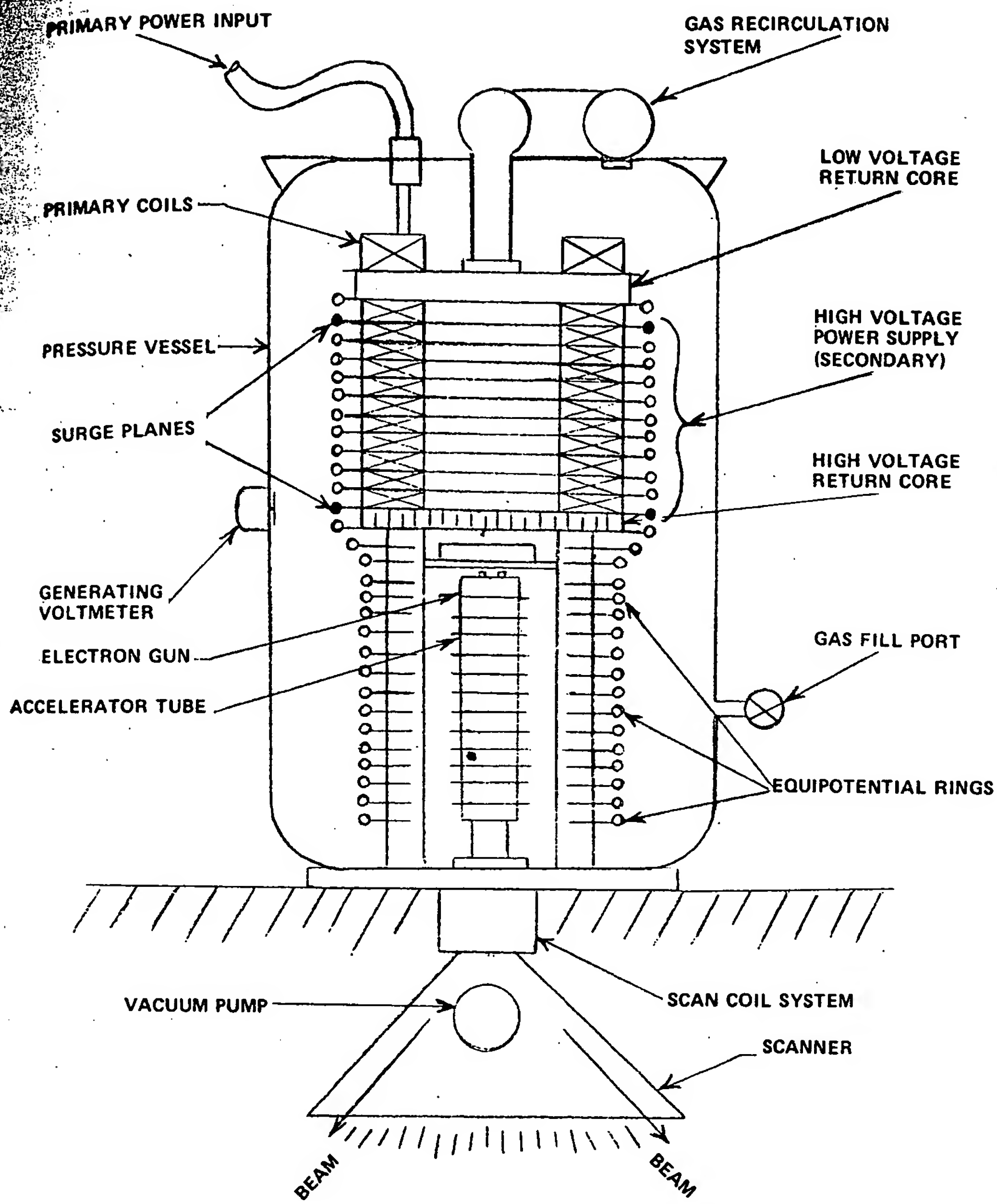

Fig. 7. Schematic - Integral Insulated Core Transformer®.

Interlock indicators are a must for personnel and equipment which could be damaged or cause damage from loss of power, water, cooling air and, more important, unrestrained ozone or radiation. Regardless of what safety devices are installed, I strongly recommend that two circuits be designed into each and every electron beam generator. One is an auxiliary primary power contactor with an independent source of control voltage with the main power in series with the contactor supplied. The second is a properly located radiation detector, interlocked in such a manner that the main power circuit is deenergized should the radiation level become excessive.
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In conjunction with the safety interlocks it is advisable to have main power and control power disconnects well identified and readily accessible to the control centers. In addition, 24-hour vacuum power circuit breakers should have locks which prevent accidental shut-off, but allow for protection during circuit overload.
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Vacuum. No matter how a radiation device is designed, what principle makes the unit function, or how sophisticated the control systems are, a particle accelerator is just so much metal, useless circuitry and plastic without an evacuated beam path. Vacuum in a beam tube must be within a suitable range to establish a mean free path to prevent electron collision. Severe voltage and beam instability, and possible damage, will result when the vacuum pressure is above 10^{-5} torr. In order to obtain a suitable operating vacuum a pump is attached to the system as close as possible to the electron source. This is really the most important area to maintain under good vacuum, but the most difficult due to the length of the accelerating path.

Various types of vacuum pumps are used by accelerator manufacturers; usually, a particular standard type is supplied unless otherwise specified by the purchaser. The most modern and common pumps used are the vacion, triode and turbomolecular pumps. The vacion and triode are electronic devices which obtain vacuum by exciting molecules through magnetism, causing them to seek an absorbing grid by developing a current flow between a high voltage source and ground. These types of pumps will not start from atmosphere and require mechanical pumps to draw a vacuum of 10^{-3} torr. Normally pump life is very long, providing they are not subjected to sudden or prolonged bursts of atmosphere. Most are protected to prevent pump or equipment damage.

The turbomolecular pump is a very high speed mechanical device which contains many rotor and stator blades. On impact with the gas and vapor particles the rotor blade impulse is transmitted to the particles, thus giving them a speed in the direction of the blade rotation supplementary to their own speed. A mechanical backing pump is required to remove the molecules from the system, and therefore must operate simultaneously with the turbomolecular pump. There is one manufactured turbomolecular pump which does not require a backing system. This type of pump is considerably faster on recovery than the electronic pump. However, in spite of the recovery aspect of the numerous turbomolecular pumps, only one of the manufacturers states that its pump can be subjected to atmosphere without damage. Severe pump destruction occurs on most turbomolecular-pump rotors when the system is allowed to atmosphere while in operation.

It is advisable to isolate the pump from the acceleration system with a high-speed electric/pneumatic vacuum gate. The gate serves to protect the expensive pump from damage in the event of a power failure or atmosphere burst, and prevents pump oil from backstreaming into the beam path.

The vacuum conditions are monitored by various methods. The simplest is accomplished with the vacion or triode pumps because the current flow within the pump itself is the gauge. Current in milliamperes, torr voltage are monitored on one meter via a selector switch. Simply, monitoring of vacuum on any gauge is accomplished by measuring current from an anode to a cathode. The higher the current the poorer the vacuum. In vacuum systems with mechanical pumps a separate gauge is required such as an ion, cold cathode, nude ion gauge, etc. Selection of the gauge is determined by the level of vacuum monitored, reliability and the user's choice.
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Window Cooling. Now that we have had a look at the accelerator itself, let us take a look at other necessities required to operate a radiation facility. One of these requirements is a blower to cool the scanner window. A low-pressure high-volume blower is all that is necessary, wired to start automatically with the high voltage circuit. The blower is piped into the plenum supplied by the vendor and, should the flow drop below a predetermined level, can be interlocked to prevent window failure.
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Ozone Removal. Any time electrons are driven into or through atmosphere at a high velocity, O_3 (ozone) is generated. The higher the power the greater the concentration of ozone. This must be removed from any occupied area, as it is hazardous to the respiratory system and deteriorates most substances except for certain stainless steels, concrete, some forms of aluminum and ceramic tile. The simplest and most effective way to rid the cell or enclosure of ozone is to exhaust the area and simultaneously draw fresh air makeup. To the best of my knowledge, an efficient, inexpensive scrubber is not available for industrial application.
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Operational Conditions. Normally, all vendors fabricate their controls with metering considered accurate and adequate to observe and operate the electron beam generator. However, there are situations requiring additional equipment in order to properly observe equipment operation in conjunction with external electrical influences. It has been my experience that these influences do occur and cannot be observed in standard metering. Therefore, high-speed recorders can aid in reducing or eliminating expensive equipment failure by displaying disturbances too fast in incidence and too short in duration for standard metering.

The recorder, although costly, may pay for itself by relating one problematic line condition. This type of equipment is strictly a user's option and is not always a necessity.
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Assuming that the generator interior has been assembled correctly, the only item left is assurance that the insulating gas (sulphur hexafluoride, SF_6) has a good dew point. A gas moisture content of -50°F or better is preferable, and is usually that dry or dryer as purchased. However, once an accelerator has been operated for a period approximating two hours at full power, moisture is released from the components. The dew point should and can be lowered by circulating the SF_6 through a molecular sieve. This can easily be accomplished remotely while the unit is running under production conditions.
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Accelerator Housing. Undoubtedly the most important consideration in planning a radiation processing facility is the cell or shielding. The two leading manufacturers of radiation production equipment offer a completely shielded, ready-to-run facility with a maximum voltage of approximately 500 kV. This is no doubt the

most convenient and inexpensive route to take. However, when planning higher e[illegible] systems a budget must be established for the housing. The important thing to re[illegible] member is the assurance of radiation integrity. Then concentrate on ozone remov[illegible] efficiency of product handling and serviceability of all equipment internal to [illegible] cell. An accelerator and associated equipment that can be serviced easily is [illegible] which will show higher productivity.

There are numerous ways to construct a cell even though the basic structure is [illegible] usually of poured concrete. It really depends on one's budget just how elaborat[illegible] the facility is designed.
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Certainly, a structure within the confines of a factory would not require "dressing up."

A cell interior should be designed for efficiency, cleanliness and appearance. [illegible] latter can be combined by using the proper materials, particularly in the "hot cell." Selection of wiring, conduits, water and air lines, and wall coverings should be carefully examined for ability to withstand the severe conditions developed by an accelerator and could end up being replaced often.
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There are many more detailed facets too numerous to mention when selecting and installing an electron beam generator. In conclusion, I would say to select the proper E.B.G., house it in a proper facility and observe proper health physics practices to obtain a proper marketable product.
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